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(54) Title: DRILLING SYSTEM AND METHOD FOR CONTROLLING EQUIVALENT CIRCULATING DENSITY DURING DRILLING OF WELLBORES

(57) Abstract: A drilling system for drilling subsea wellbores includes a tubing-conveyed drill bit (130) that passes through a subsea wellhead. Surface supplied drillng fluid flows through the tubing (121), discharges at the drill bit, returns to the wellhead through a wellbore annulus (122), and flows to the surface via a riser (160) extending from the wellhead. A flow restriction device (164) positioned in the riser restricts the flow of the returning fluid while an active fluid device controllably discharges fluid from a location below to just above the flow restriction device in the riser, thereby controlling bottomhole pressure and equivalent circulating density ("ECD"). Alternatively, the fluid is discharged into a separate return line (206) thereby providing dual gradient drilling while controlling bottomhole pressure and ECD. A controller (180) controls the energy and thus the speed of the pump in response to downhole measurement(s) to maintain the ECD at a predetermined value or within a predetermined range.

DRILLING SYSTEM AND METHOD FOR CONTROLLING EQUIVALENT CIRCULATING DENSITY DURING DRILLING OF WELLBORES

CROSS-REFERENCES TO RELATED APPLICATIONS

This application takes priority from Provisional U.S. Patent Applications Serial Nos. 60/303,959 and 60/304,160, filed on July 9th, 2001 and July 10th, 2001, respectively, and Provisional U.S. Patent Application Serial No. 60/323,797, filed on Sept 20th, 2001. This application also takes priority from U.S. Application Serial Nos. 10/094,208, filed Mar. 8th, 2002 and 09/353,275, filed July 14th, 1999, both of which claim priority from U.S. Application Nos.: 60/108,601, filed Nov. 16th, 1998; 60/101,541, filed Sept. 23rd, 1998; 60/092,908, filed July 15th, 1998; and 60/095,188, filed Aug. 3rd, 1998.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to oilfield wellbore drilling systems and more particularly to subsea drilling systems that control bottom hole pressure or equivalent circulating density during drilling of the wellbores.

Background of the Art

Oilfield wellbores are drilled by rotating a drill bit conveyed into the wellbore by a drill string. The drill string includes a drilling assembly (also referred to as the "bottom hole assembly" or "BHA") that carries the drill bit. The BHA is conveyed into the wellbore by a tubing. Coiled tubing or jointed tubing is utilized to convey the drilling assembly into the wellbore. The drilling assembly sometimes includes a drilling motor or a "mud motor" that rotates the drill bit. The drilling assembly also includes a variety of sensors for taking measurements of a variety of drilling, formation and BHA parameters. A suitable drilling fluid

(commonly referred to as the "mud") is supplied or pumped from the surface down the tubing. The drilling fluid drives the mud motor and then it discharges at the bottom of the drill bit. The drilling fluid returns uphole via the annulus between the drill string and the wellbore and carries with it pieces of formation (commonly referred to as the "cuttings") cut or produced by the drill bit in drilling the wellbore.

For drilling wellbores under water (referred to in the industry as "offshore" or "subsea" drilling) tubing is provided at the surface work station (located on a vessel or platform). One or more tubing injectors or rigs are used to move the tubing into and out of the wellbore. In sub-sea riser-type drilling, a riser, which is formed by joining sections of casing or pipe, is deployed between the drilling vessel and the wellhead equipment at the sea bottom and is utilized to guide the tubing to the wellhead. The riser also serves as a conduit for fluid returning from the wellhead to the vessel at sea surface.

During drilling, the drilling operator attempts to carefully control the fluid density at the surface so as to prevent an overburdened condition in the wellbore. In other words, the operator maintains the hydrostatic pressure of the drilling fluid in the wellbore above the formation or pore pressure to avoid well blow-out. The density of the drilling fluid and the fluid flow rate largely determine the effectiveness of the drilling fluid to carry the cuttings to the surface. One important downhole parameter during drilling is the bottomhole pressure, which is effectively the equivalent circulating density ("ECD") of the fluid at the wellbore bottom.

This term, ECD, describes the condition that exists when the drilling mud in the well is circulated. ECD is the friction pressure caused by the fluid circulating through the annulus of the open hole and the casing(s) on its way back to the surface. This causes an increase in the pressure profile along this

path that is different from the pressure profile when the well is in a static condition (i.e., not circulating). In addition to the increase in pressure while circulating, there is an additional increase in pressure while drilling due to the introduction of drill solids into the fluid. This pressure increase along the annulus of the well can negatively impact drilling operations by fracturing the formation at the shoe of the last casing. This can reduce the amount of hole that can be drilled before having to set an additional casing. In addition, the rate of circulation that can be achieved is also limited. Due to this circulating pressure increase, the ability to clean the hole is severely restricted. This condition is exacerbated when drilling an offshore well. In offshore wells, the difference between the fracture pressures in the shallow sections of the well and the pore pressures of the deeper sections is considerably smaller compared to on-shore wellbores. This is due to the seawater gradient versus the gradient that would exist if there were soil overburden for the same depth.

In order to be able to drill a well of this type to a total wellbore depth at a subsea location, the bottom hole ECD must be reduced or controlled. One approach to do so is to use a mud filled riser to form a subsea fluid circulation system utilizing the tubing, BHA, the annulus between the tubing and the wellbore and the mud filled riser, and then inject gas (or some other low density liquid) in the primary drilling fluid (typically in the annulus adjacent the BHA) to reduce the density of fluid downstream (i.e., in the remainder of the fluid circulation system). This so-called "dual density" approach is often referred to as drilling with compressible fluids.

Another method for changing the density gradient in a deepwater return fluid path has been proposed. This approach proposes to use a tank, such as an elastic bag, at the sea floor for receiving return fluid from the wellbore annulus and holding it at the hydrostatic pressure of the water at the sea floor. Independent of the flow in the annulus, a separate return line connected to the

sea floor storage tank and a subsea lifting pump delivers the return fluid to the surface. Although this technique (which is referred to as "dual gradient" drilling) would use a single fluid, it would also require a discontinuity in the hydraulic gradient line between the sea floor storage tank and the subsea lifting pump. This requires close monitoring and control of the pressure at the subsea storage tank, subsea hydrostatic water pressure, subsea lifting pump operation and the surface pump delivering drilling fluids under pressure into the tubing for flow downhole. The level of complexity of the required subsea instrumentation and controls as well as the difficulty of deployment of the system has delayed the commercial application of the "dual gradient" system.

Another approach is described in U.S. Patent Application No. 09/353,275, filed on July 14, 1999 and assigned to the assignee of the present application. The U.S. Patent Application No. 09/353,275 is incorporated herein by reference in its entirety. One embodiment of this application describes a riserless system wherein a centrifugal pump in a separate return line controls the fluid flow to the surface and thus the equivalent circulating density.

The present invention provides a wellbore system wherein equivalent circulating density is controlled by controllably bypassing the returning fluid about a restriction in the returning fluid path of a riser utilizing an active differential pressure device, such as a centrifugal pump or turbine, located adjacent to the riser. The fluid is then returned into the riser above the restriction. The present invention also provides a dual gradient subsea drilling system wherein equivalent circulating density is controlled by controllably bypassing the returning fluid about a restriction in a riser by utilizing an active differential pressure device, such as a centrifugal pump or turbine located some distance above the sea bed. The present systems are relatively easy to incorporate in new and existing systems.

SUMMARY OF THE INVENTION

The present invention provides wellbore systems for performing subsea downhole wellbore operations, such as subsea drilling as described more fully hereinafter. Such drilling systems include a rig at the sea level that moves a drill string into and out of the wellbore. A bottom hole assembly, carrying the drill bit, is attached to the bottom end of the tubing. A wellhead assembly or equipment at the sea bottom receives the bottom hole assembly and the tubing. A drilling fluid system supplies a drilling fluid into a fluid circuit that supports wellbore operations. In one embodiment, the fluid circuit includes a supply conduit and a return conduit. The supply conduit includes a tubing string that receives drilling fluid from the fluid system. This fluid is discharged at the drill bit and returns to the wellhead equipment carrying the drill cuttings. The return conduit includes a riser dispersed between the wellhead equipment and the surface that guides the drill string and provides a conduit for moving the returning fluid to the surface.

In one embodiment of the present invention, a flow restriction device in the riser restricts the flow of the returning fluid through the riser. Preferably, the flow restriction device moves between a substantially open bore and closed bore positions and accommodates the axial sliding and rotation movement of the drill string. In one embodiment, radial bearings stabilize the drill string while a hydraulically actuated packer assembly provides selective obstruction of the riser bore and therefore selectively diverts return fluid flow into a flow diverter line provided below the flow restriction device. Additionally, a seal such as a rotary seal is used to further restrict flow of return fluid through the flow restriction device. A fluid flow device, such as a centrifugal pump or turbine in the flow diverter line causes a pressure differential in the returning fluid as it flows from just below the flow restriction device to above the flow restriction device. The pump speed is controlled, by controlling the energy input to the pump. One or more pressure sensors provide pressure measurement of the circulating fluid. A controller controls the operation of the pump to control the amount of the

differential pressure across the pump and thus the equivalent circulating density. The controller maintains the equivalent circulating density at a predetermined level or within a predetermined range in response to programmed instructions provided to the controller. The pump is mounted on the outside of the riser joint, typically at a sufficient depth below the sea level to provide enough lift to offset the desired amount of ECD. Alternatively, the flow restriction device and the pump may be disposed in the return fluid path in the annulus between the wellbore and the drill string. The present system is equally useful as an at-balance or an underbalanced drilling system.

In another embodiment of the present invention, a flow restriction device in the riser restricts the flow of the returning fluid through the riser. A flow diverter line, active pressure differential device ("APD Device") and a separate return line provide a fluid flow path around the flow restriction device. In this embodiment, dual gradient drilling with active control of wellbore pressure is achieved mid riser or at a selected point in the riser, the selected point between the surface and sea bottom. The active pressure differential device, such as centrifugal pumps or turbines, moves the returning fluid from just below the flow restriction device to the surface via the separate return line. The operation of the active pressure differential device is controlled to create a differential pressure across the device, thereby reducing the bottomhole pressure. The pumps or turbines speeds are controlled, by controlling the energy input to the pumps or turbines. One or more pressure sensors provide pressure measurements of the circulating fluid. A controller controls the operation of the pumps or turbines to control the amount of the pressure differential and thus the equivalent circulating density. The controller maintains the bottom hole pressure and the equivalent circulating density at a predetermined level or within a predetermined range in response to programmed instructions provided to the controller. The pumps or turbines are mounted on the outside of the riser, typically between 1000 to 3000 ft. below sea level, but above

the sea bed. The present system is equally useful in maintaining the bottomhole pressure at an at-balance or under-balance condition.

Examples of the more important features of the invention have been summarized (albeit rather broadly) in order that the detailed description thereof that follows may be better understood and in order that the contributions they represent to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, reference should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawing:

Figure 1 is a schematic elevation view of one embodiment of a wellbore system for controlling equivalent circulating density during drilling of subsea wellbores;

Figure 2 is a schematic elevation view of a flow restriction device and active differential pressure device made in accordance with one embodiment of the present invention;

Figures 3A and **3B** illustrate pressure gradient curves provided by the **Figure 1** embodiment of the present invention;

Figure 4 is a schematic elevation view of one embodiment of a wellbore system for controlling equivalent circulating density and bottomhole pressure during dual gradient drilling of subsea wellbores with the device mounted at a point in the riser between the surface and the seabed; and

Figures 5A and **5B** illustrate pressure gradient curves provided by the **Figure 4** embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 1 shows a schematic elevational view of a wellbore drilling system **100** for drilling a subsea or under water wellbore **90**. The drilling system **100** includes a drilling platform **101**, which may be a drill ship or another suitable surface work station such as a floating platform or a semi-submersible. A drilling ship or a floating rig is usually preferred for drilling deep water wellbores, such as wellbores drilled under several thousand feet of water. To drill a wellbore **90** under water, wellhead equipment **125** is deployed above the wellbore **90** at the sea bed or bottom **123**. The wellhead equipment **125** includes a blow-out-preventer stack **126**. A lubricator (not shown) with its associated flow control valves may be provided over the blow-out-preventer **126**.

The subsea wellbore **90** is drilled by a drill bit **130** carried by a drill string **120**, which includes a drilling assembly or a bottom hole assembly ("BHA") **135** at the bottom of a suitable tubing **121**, which may be a coiled tubing or a jointed pipe. The tubing **121** is placed at the drilling platform **101**. To drill the wellbore **90**, the BHA **135** is conveyed from the vessel **101** to the wellhead equipment **125** and then inserted into the wellbore **90**. The tubing **121** is moved to the wellhead equipment **125** and then moved into and out of the wellbore **90** by a suitable tubing injection system.

To drill the wellbore **90**, a drilling fluid **20** from a surface drilling fluid system or mud system **22** is directed into a fluid circuit that services the wellbore **90**. This fluid can be pressurized or use primarily gravity assisted flow. In one embodiment, the mud system **22** includes a mud pit or supply source **26** and one or more pumps **28** in fluid communication with a supply conduit of the fluid circuit. The fluid is pumped down the supply conduit, which includes the tubing **121**. The drilling fluid **20** may operate a mud motor in the BHA **135**, which in turn rotates the drill bit **130**. The drill bit **130** breaks or cuts the formation (rock) into cuttings **147**. The drilling fluid **142** leaving the drill bit travels uphole through a return

conduit of the fluid circuit. In one embodiment, the return conduit includes the annulus **122** between the drill string **120** and the wellbore wall **126** carrying the drill cuttings **147**. The return circuit also includes a riser **160** between the wellhead **125** and the surface **101** that carries the returning fluid **142** from the wellbore **90** to the sea level. The returning fluid **142** discharges into a separator **24**, which separates the cuttings **147** and other solids from the returning fluid **142** and discharges the clean fluid into the mud pit **26.** The tubing **121** passes through the mud-filled riser **160**. As shown in **Figure 1**, the clean mud **20** is pumped through the tubing **121** and the mud **142** with cuttings **147** returns to the surface via the annulus **122** up to the wellhead **125** and then via the riser **160.** Thus, the fluid circulation system or fluid circuit includes a supply conduit (e.g., the tubing **121**) and a return conduit (e.g., the annulus **122** and the riser **160**). Thus, in one embodiment the riser constitutes an active part of the fluid circulation system.

As noted above, the present invention provides a drilling system for controlling wellbore pressure and controlling or reducing the ECD effect during drilling fluid circulation or drilling of subsea wellbores. To achieve the desired control of the ECD, the present invention selectively adjusts the pressure gradient of the fluid circulation system. One embodiment of the present invention utilizes an arrangement wherein the flow of return fluid is controlled (e.g., assisted) at a predetermined elevation along the riser **160**. An exemplary arrangement of such an embodiment includes a flow restriction device **164** in the drilling riser **160** and an actively controlled fluid lifting device **170.**

Referring now to **Figure 2**, an exemplary flow restriction device **164** diverts return fluid flow from the riser **160** to the fluid lifting device **170.** Preferably, the flow restriction device **164** can move between a substantially open bore position (no flow restriction) and a substantially closed bore position (substantial flow restriction). It is also preferred that the flow restriction device

164 accommodate both the axial sliding and rotation movement of the drill string **121** when in the substantially closed position. Accordingly, in a preferred embodiment of the flow restriction device **164**, upper and lower radial bearings **164A, 164B** are used to stabilize the drill string **121** during movement. Further, a hydraulically actuated packer assembly **164D** provides selective obstruction of the bore of the riser **160**. When energized with hydraulic fluid via a hydraulic line **164G**, the inflatable elements of the packer assembly **164D** expand to grip the drill string **121** and thereby substantially divert return fluid flow **142** into the diverter line **171**. Intermediate elements such as concentric tubular sleeve bearings (not shown) can be interposed between the packer assembly **164D** and the drill string **121**. Additionally, a seal **164C** such as a rotary seal can be provide an additional barrier against the flow of return fluid **142** through the flow restriction device **164**. When de-energized, the packer assembly **164D** disengages from the drill string **121** and retracts toward the wall of the riser **160**. This retraction reduces the obstruction of the bore of the riser **160** and thereby enables large diameter equipment (not shown) to cross the flow restriction device **164** while, for example, the drill string **121** is tripped in and out of the riser **160**. Preferably, the flow restriction device **164** is positioned in a housing joint **164F**, which can be a slip joint housing. Elements such as the bearings **164A,B** and seal **164C** can be configured to reside permanently in the housing joint **164F** or mount on the drill string **121**. In one preferred arrangement, element that are subjected to relatively high wear are positioned on the drill string **121** and changed out when the drill string **121** is tripped. Furthermore, a certain controlled clearance is preferably provided between the drill string **121** and the flow restriction device **164** so that upset portion of the drill string **121** (e.g., jointed connections) can slide or pass through the flow restriction device **164**.

The flow restriction device **164** may be adjustable from a surface location via a control line **165**, which allows the control over the pressure differential through the riser. The depth at which the flow restriction device **164** is installed

will depend upon the maximum desired reduction in the ECD. A depth of between 1000 ft to 3000 ft. is considered adequate for most subsea applications. The returning fluid **142** in the riser **160** is diverted about the restriction device **164** by a fluid lifting device, such as centrifugal pump **170** coupled to a flow cross line or a diverter line **171**. The diverter line **171** is installed from a location below the flow restriction device **164** to a location above the flow restriction device **164**. Thus, the lifting device **170** diverts the returning fluid in the riser from below the flow restriction device to above the flow restriction device **164**. The fluid lifting device **170** is mounted on the exterior of the riser **160**. To control the ECD at a desired value, the pump speed (RPM) is controlled. Typically, the energy input to (and thus the RPM of) the pump **170** is increased as the fluid flow in the circulating path is increased and/or the length of the circulating path increases with advancement of the drill bit. Moreover, the energy input to (and thus the RPM of) the lifting device is decreased as the return flow in the well **90 (Fig. 1)** is decreased. In this configuration, the lifting device takes on part of the work of pushing or lifting the drilling fluid back to the surface from the restriction device location. The energy input into the lifting device **170** (i.e. the work performed by the device) results in reducing the hydrostatic pressure of the fluid column below that point, which results in a corresponding reduction of the pressure along the return path in the annulus below the lifting device **170** and more specifically at the shoe **151** of the last casing **152**. Any number of devices such as centrifugal pumps, turbines, jet pumps, positive displacement pumps and the like can be suitable for providing a pressure differential and associated control of ECD. The terms active pressure differential device ("APD" device), active fluid flow device and active fluid lifting device are intended to encompass at least such devices, mechanisms and arrangements.

Referring now to **Figure 1**, in an alternative embodiment, the flow restriction device **164** and the pump **170** may be installed at a suitable location in the wellbore annulus, such as shown by arrow **175**, or at the wellhead equipment

125. Also, the present invention is equally applicable to under-balanced drilling systems since it is capable of controlling the ECD effect to a desired level.

Referring now to **Figures 1** and **2**, the wellbore system **100** further includes a controller **180** at the surface that is adapted to receive input or signals from a variety of sensors including those in remote equipment such as the BHA **135**. The system **100** includes one or more pressure sensors, such as P_1 and a host of other sensors S_{1-7} that provide measurements relating to a variety of drilling parameters, such as fluid flow rate, temperature, weight-on bit, rate of penetration, etc., drilling assembly or BHA parameters, such as vibration, stick slip, RPM, inclination, direction, BHA location, etc. and formation or formation evaluation parameters commonly referred to as measurement-while-drilling parameters such as resistivity, acoustic, nuclear, NMR, etc. Drilling fluid pressure measurements may also be obtained at wellhead (P_2) and at the surface (P_3) or at any other suitable location (P_n) along the drill string **120**. Further, the status and condition of equipment as well as parameters relating to ambient conditions (as well as pressure and other parameters listed above) in the system **100** can be monitored by sensors positioned throughout the system **100**: exemplary locations including at the surface (**S1**), at the fluid lifting device (**S2**), at the wellhead equipment **125** (**S3**), at the fluid restriction device **164** (**S4**), near the casing shoe **151B** (**S5**), at bottomhole assembly (**S6**), and near the inlet to the active fluid lifting device **170** (**S7**). The data provided by these sensors are transmitted to the controller **180** by a suitable telemetry system (not shown).

During drilling, the controller **180** receives the pressure information from one or more of the sensors (P_1 - P_n) and/or information from other sensors (S_1-S_7) in the system **100**. The controller **180** determines the ECD and adjusts the energy input to the lifting device **170** to maintain the ECD at a desired or predetermined value or within a desired or predetermined range. The controller **180** includes a microprocessor or a computer, peripherals **184** and programs

which are capable of making online decisions regarding the control of the flow restriction device **164** and the energy input to the lifting device **170**. A speed sensor $\mathbf{S_2}$ may be used to determine the pump speed. Thus, the location of the flow restriction device **164** and the pressure differential about the restriction device controls the ECD. The wellbore system **100** thus provides a closed loop system for controlling the ECD by controllably diverting the returning fluid about a flow restriction device in the returning fluid path in response to one or more parameters of interest during drilling of a wellbore. This system is relatively simple and efficient and can be incorporated into new or existing drilling systems.

Referring now to **Figures 3A and 3B**, there is graphically illustrated the ECD control provided by the above-described embodiment of the present invention. For convenience, **Figure 3A** shows the fluid lifting device **164** at a depth **D1** and a representative location in the wellbore such as the casing shoe **151** at a lower depth **D2**. **Figure 3B** provides a depth versus pressure graph having a first curve **C1** representative of a pressure gradient before operation of the system **100** and a second curve **C2** representative of a pressure gradients during operation of the system **100**. Curve **C3** represents a theoretical curve wherein the ECD condition is not present; *i.e.*, when the well is static and not circulating and is free of drill cuttings. It will be seen that a target or selected pressure at depth **D2** under curve **C3** cannot be met with curve **C1**. Advantageously, the system **100** reduces the hydrostatic pressure at depth **D1** and thus shifts the pressure gradient as shown by curve **C3**, which can provide the desired predetermined pressure at depth **D2**. This shift is roughly the pressure drop provided by the fluid lifting device **170**.

Referring now to **Figure 4**, there is shown another embodiment of the present invention that is suitable for dual gradient drilling. Features the same as those in **Figure 1** are, for convenience, referenced with the same numerals. The **Figure 4** embodiment includes a system **200** wherein the returning fluid **142**

in the riser **160** is diverted about the restriction device **164** by an active pressure differential device **202** coupled to a flow cross line or a diverter line **204**. The diverter line **204** is installed at a location below the flow restriction device **164**. Thus, the active pressure differential device **202** diverts the returning fluid **142** in the riser **160** from below the flow restriction device **164** to the surface. The active pressure differential device **202** is mounted above the seabed and external to riser **160**. The operation of the active pressure differential device **202** creates a selected pressure differential across the device **202**. It also moves the returning fluid **142** from just below the flow restriction device **164** and discharges the diverted fluid into a separate return line **206**, which carries the fluid to the surface by bypassing the portion of the riser **160** that is above the flow restriction device **164**. **Figure 4** further illustrates a material **208**, having a lower density than the return fluid and obtained from a suitable source at or near the surface, is maintained in the riser **160** uphole of restriction device **164**. The material **208** usually is seawater. However, a suitable fluid could have a density less or greater than seawater. The material **208** is used in providing a static pressure gradient to the wellbore that is less than the pressure gradient formed by the fluid downhole of the flow restriction device **164**. Drilling is performed in a similar manner to that described with respect to the **Figure 1** embodiment except that the active pressure differential device **202** discharges the return fluid **142** into the separate return line **206** that may be external to the riser **160**. Thereafter, the return fluid **142** is discharged into the separator **24.**

To achieve the desired reduction and/or control of the bottomhole pressure or ECD, the system **200** utilizes a flow restriction device **164** and active pressure differential device **202** in much the same manner as that described in reference to system **100** (**Figure 1**). That is, briefly, the active pressure differential device **202** provides lift to the return fluid, above its location reducing the hydrostatic pressure of the fluid column below that point. This results in a corresponding reduction of the pressure along the return path and more

specifically at the shoe **151** of the last casing **152**. Therefore, control of the active pressure differential device allows for control of the wellbore pressure and ECD.

Referring now to **Figures 5A and 5B**, there is graphically illustrated the ECD control provided by the above-described embodiment of the present invention. For convenience, **Figure 5A** shows the fluid lifting device **202** at a depth **D3** and a representative location in the wellbore such as the casing shoe **151** at a lower depth **D4**. **Figure 5B** provides a depth versus pressure chart having a first curve **C4** representative of a pressure gradient before operation of the system **100** and a second curve **C5** representative of a pressure gradients during operation of the system **100**. Curve **C6** represents a theoretical curve wherein the ECD condition is not present; *i.e.*, when the well is static and not circulating and is free of drill cuttings. The pressure gradient of the non-drilling fluid material **208** (*e.g.*, seawater) (**Fig. 3**) in riser is shown as curve **C7** and the pressure gradient of the drilling fluid in the separate line **206** (**Fig. 3**) is shown as curve **C8**. It will be seen that a target or selected pressure at depth **D3** under curve **C6** cannot be met with curve **C4**. Advantageously, the system **200** reduces the hydrostatic pressure at depth **D3** and thus shifts the pressure gradient curve as shown by curve **C5**, which can provide the desired predetermined pressure at depth **D4**. This shift is roughly the pressure drop provided by the fluid lifting device **202**.

Like the wellbore system **100** of **Figure 1**, the system **200** includes a controller **180** that is adapted to receive input or signals from a variety of sensors including those in the BHA **135**. For brevity, the details of the several associated components will not be repeated. Further, also like system **100**, the controller **180** of system **200** receives the pressure information from one or more of the sensors (**P_1 – P_n**) and/or information from other sensors **S1-S7** in the system **100**. The controller **180** determines the bottomhole pressure and adjusts the energy input to the pressure differential device **202** to maintain the bottomhole

pressure at a desired or predetermined value or within a desired or predetermined range. The wellbore system **200** thus provides a closed loop system for controlling the ECD by controllably diverting the returning fluid about a flow restriction device in the returning fluid path in response to one or more parameters of interest during drilling of a wellbore. This system is relatively simple and efficient and can be incorporated into new or existing drilling systems.

While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

WHAT IS CLAIMED IS:

1. A system for supporting subsea wellbore operations, comprising:
   (a) a supply conduit for providing drilling fluid into a wellbore;
   (b) a return conduit including a riser for conveying the drilling fluid from the wellbore to a predetermined location, the supply conduit and return conduit forming a fluid circuit; and
   (c) an active pressure differential device ("APD device") adapted to selectively receive the drilling fluid from a first selected location on the riser and convey the drilling fluid to a second selected location.

2. The system according to claim 1 further comprising a flow restriction device positioned in the return conduit for selectively diverting the drilling fluid from the riser to the APD device.

3. The system according to claim 1 wherein the second selected location is one of (i) a section of the riser uphole of the first selected location; and (ii) a separate line to a surface location.

4. The system according to claim 1 wherein the second selected location is a separate line to a surface location; and a section of the riser uphole of the first selected location is at least partially filled with a fluid having a density different from that of the drilling fluid.

5. The system of claim 1, wherein the APD device is located at one of (i) in the riser, (ii) outside the riser, and (iii) in an annulus of the wellbore.

6. The system of claim 1, wherein the APD device is between 1000 ft. below the sea level and the sea bottom.

7. The system of claim 1, wherein the APD device is one of: (i) at least one centrifugal pump; (ii) a turbine; (iii) jet pump; and (iv) a positive displacement pump.

8. The system according to claim 1 wherein the APD device is configured to control equivalent circulating density of the drilling fluid in at least a portion of the fluid circuit.

9. The system of claim 1 further comprising a controller that controls the APD device to control the equivalent circulating density in at least a portion of the fluid circuit.

10. The system of claim 9, wherein the controller controls the APD device in response to pressure.

11. The system of claim 10, wherein the pressure is one of: (i) bottomhole pressure; (ii) measured at a location in the supply conduit; (iii) measured at well control equipment associated with the wellbore; (iv) measured in the return conduit; (v) measured in a bottomhole assembly; (vi) measured at the surface; (vii) stored in a memory associated with the controller; and (viii) measured near an inlet to the APD device.

12. The system of claim 9, wherein the controller controls the differential pressure to one of: (i) maintain the bottomhole pressure at a predetermined value; (ii) maintain the bottomhole pressure within a range; (iii) maintain the pressure in the wellbore at at-balance condition; (iv) maintain the pressure in the wellbore at under-balance condition; and (v) reduce the bottomhole pressure by a selected amount.

13. The system of claim 9, wherein the controller controls the APD device to maintain the equivalent circulating density at one of (i) a predetermined value, and (ii) within a predetermined range.

14. The system of claim 9 further comprising at least one sensor providing pressure measurements of the drilling fluid in the fluid circuit.

15. The system of claim 14, wherein the controller controls the APD device in response to the pressure measurement and according to programmed instructions provided thereto.

16. The system of claim 1 further comprising drill string disposed in the wellbore; and a drilling assembly connected to the drill string for forming the wellbore.

17. The system of claim 1 wherein a controller operably coupled to the APD device controls the APD device in response to a parameter of interest.

18. The system of claim 17, wherein the parameter of interest is one of: (i) pressure; (ii) flow rate; (iii) characteristic of fluid in the wellbore; and (iv) a formation characteristic.

19. A method for supporting subsea wellbore operations, comprising:

(a) providing drilling fluid into a wellbore via a supply conduit;

(b) conveying the drilling fluid from the wellbore to a predetermined location via a return conduit including a riser, the supply conduit and return conduit forming a fluid circuit; and

(c) conveying the drilling fluid from a first selected location on the riser to a second selected location with an active pressure differential device ("APD device").

20. The method according to claim 19 further comprising selectively diverting the drilling fluid from the riser to the APD device with a flow restriction device positioned in the return conduit.

21. The method according to claim 19 wherein the second selected location is one of (i) a section of the riser uphole of the first selected location; and (ii) a separate line to a surface location.

22. The method according to claim 19 wherein the second selected location is a separate line to a surface location; and a section of the riser uphole of the first selected location is at least partially filled with a fluid having a density different from that of the drilling fluid.

23. The method according to claim 19, further comprising positioning the APD device between 1000 ft. below the sea level and the sea bottom.

24. The method of claim 19, wherein the APD device is one of: (i) at least one centrifugal pump; (ii) a turbine; (iii) a jet pump and (iv) a positive displacement pump.

25. The method of claim 19 further comprising controlling the APD device to control the equivalent circulating density in at least a portion of the fluid circuit.

26. The method of claim 25, wherein the APD device is controlled in response to pressure.

27. The method of claim 26, wherein the pressure is one of: (i) bottomhole pressure; (ii) measured at a location in the supply conduit; (iii) measured at well control equipment associated with the wellbore; (iv) measured in the return conduit; (v) measured in a bottomhole assembly; (vi) measured at the surface;

(vii) stored in a memory associated with the controller; and (viii) measured near an inlet to the APD device.

28. The method of claim 19, further comprising controlling the APD device to provide a differential pressure to control a bottomhole pressure to one of: (i) maintain the bottomhole pressure at a predetermined value; (ii) maintain the bottomhole pressure within a range; (iii) maintain the pressure in the wellbore at at-balance condition; (iv) maintain the pressure in the wellbore at under-balance condition; and (v) reduce the bottomhole pressure by a selected amount.

29. The method according to claim 19, wherein the controller controls the fluid flow device to maintain the equivalent circulating density at one of (i) a predetermined value, and (ii) within a predetermined range.

30. The method according to claim 19 further comprising drill string disposed in the wellbore; and a drilling assembly connected to the drill string.

31. A wellbore system for performing subsea downhole wellbore operations comprising:

(a) a tubing receiving fluid from a source adjacent an upper end of the tubing;

(b) a subsea wellhead assembly above a wellbore receiving the tubing, said wellhead assembly adapted to receive said fluid after it has passed down through said tubing and back up through an annulus between the tubing and the wellbore;

(c) a riser extending up from the wellhead assembly to the sea level for conveying returning fluid from the wellhead to the sea level, with the tubing, annulus, wellhead and the riser forming a subsea fluid circulation system;

(d) a flow restriction device adapted to restrict flow of the fluid returning to the sea level; and

(e) a fluid flow device for diverting returning fluid about the flow restriction device to control equivalent circulating density of fluid circulating in the fluid circulation system.

32. The wellbore system of claim 31, wherein the active fluid flow device is located at one of (i) in the riser, (ii) outside the riser, and (iii) in the annulus.

33. The wellbore system of claim 31, wherein the active fluid flow device is one of: (i) at least one centrifugal pump; (ii) a turbine; (iii) and (iv) a positive displacement pump.

34. The wellbore system of claim 31 further comprising a controller that controls the fluid flow device to control the equivalent circulating density.

35. The wellbore system of claim 34, wherein the controller controls the active flow fluid device in response to pressure, the pressure being one of: (i) bottomhole pressure; (ii) measured at a location in the drill string; (iii) measured at the well control equipment; (iv) measured in the riser; (v) measured in a bottomhole assembly carrying the drill bit; (vi) measured at the surface; (vii) stored in a memory; and (viii) measured near the inlet to the active fluid flow device.

36. The wellbore system of claim 34, wherein the controller controls the differential pressure to control the bottomhole pressure to one of: (i) maintain the bottomhole pressure at a predetermined value; (ii) maintain the bottomhole pressure within a range; (iii) maintain the pressure in the wellbore at at-balance condition; (iv) maintain the pressure in the wellbore at under-balance condition; and (v) reduce the bottomhole pressure by a selected amount.

37. The wellbore system of claim 34, wherein the controller controls the fluid flow device to maintain the equivalent circulating density at one of (i) a predetermined value, and (ii) within a predetermined range.

38. The wellbore system of claim 34, wherein the controller controls the fluid flow device in response to pressure measurement provided by a sensor positioned in the drilling fluid and according to programmed instructions provided thereto.

39. The wellbore system of claim 31, wherein the active fluid flow device returns the returning fluid to the surface via the riser.

40. The wellbore system of claim 31 further comprising a drilling assembly connected to the tubing for forming a wellbore.

41. A method for drilling a subsea wellbore wherein a riser extends from a well control equipment at the sea bed to the surface, comprising:

(a) providing a drill string having a drill bit at a bottom end thereof extending from the surface into the wellbore through the riser;

b) supplying drilling fluid to the drill string, said drilling fluid discharging at the bottom of the drill bit and returning to the surface via an annulus between the drill string and the riser, the annulus defining a portion of the return fluid path;

(c) restricting the return fluid path in the riser at a preselected depth; and

(d) diverting returning fluid about the restriction to control equivalent circulating density of fluid at least downhole of the restriction.

42. The method of claim 41, wherein pumping is performed by an active fluid flow device.

43. The method of claim 41 further comprising returning the return fluid to the surface via a portion of the riser above the restriction.

44. The method of claim 41 further comprising controlling the diverting of the fluid with an active fluid flow device to create a selected pressure differential across the active fluid flow device.

45. The method of claim 44 further comprising providing at least one pressure sensor to provide signals indicative of pressure in the wellbore.

46. The method of claim 45 further comprising locating the at least one pressure sensor at one of: (i) the annulus of the wellbore; (ii) a location in the drill string; (iii) well control equipment; (iv) the riser; (v) a bottomhole assembly carrying the drill bit; (vi) the surface; (vii) a memory; and (viii) near the inlet of the active fluid flow device.

47. The method of claim 41, further comprising controlling the active fluid flow device to one of: (i) maintain bottomhole pressure at a certain value; (ii) maintain bottomhole pressure within a range; (iii) maintain wellbore at at-balance condition; and (iv) maintain wellbore at underbalance condition.

48. A dual gradient drilling system for drilling a subsea wellbore, the system having a riser extending from a well control equipment at the sea bed over the wellbore to the surface, comprising:

(a) a drill string having a drill bit at a bottom end thereof extending from the surface into the wellbore through the riser and the well control equipment for drilling the wellbore;

(b) a source of drilling fluid supplying drilling fluid into the drill string, said drilling fluid discharging at the bottom of the drill bit and returning to the surface in part via an annulus between the drill

string and the riser, said annulus defining the return fluid path;

(c) a restriction device at a predetermined depth in the riser restricting the flow of the returning fluid through the riser uphole of the restriction device;

(d) an active pressure differential device ("APD Device") on the riser pumping fluid from a location downhole of the restriction device to the surface by bypassing the riser section uphole of the restriction device; and (e) a fluid with density less than that of the returning fluid ("lower density fluid") in the riser uphole of the restriction device.

49. The system of claim 48, wherein the APD Device is one of: (i) at least one centrifugal pump; (ii) a turbine; (iii) and (iv) a positive displacement pump.

50. The system of claim 48 further comprising a separate return line outside the riser extending from the APD Device to the surface to carry the returning fluid to the surface by bypassing the riser.

51. The system of claim 48 further comprising a controller for controlling the APD Device to create a pressure differential across the APD Device to reduce a selected pressure associated with the drilling fluid.

52. The system of claim 48, further comprising a controller associated with the APD device to control the differential pressure to one of: (i) maintain the bottomhole pressure at a predetermined value; (ii) maintain the bottomhole pressure within a range; (iii) maintain the pressure in the wellbore at at-balance condition; (iv) maintain the pressure in the wellbore at under-balance condition; and (v) reduce the bottomhole pressure by a selected amount.

53. The system of claim 48, further comprising a controller for controlling the APD Device in response to one of: (i) a parameter of interest; (ii) programmed instruction stored for use by the controller; and (iii) signals transmitted to the controller from a remote device.

54. A dual gradient drilling method for drilling a subsea wellbore wherein a riser extends from a well control equipment at the sea bed to the surface, comprising:

(a) providing a drill string having a drill bit at a bottom end thereof extending from the surface into the wellbore through the riser;

b) supplying drilling fluid to the drill string, said drilling fluid discharging at the bottom of the drill bit and returning to the surface in part via an annulus between the drill string and the riser, said annulus defining a portion of the return fluid path;

(c) restricting the return fluid path in the riser at a preselected depth;

(d) pumping fluid from the riser at a location downhole of the restriction to the surface by bypassing the riser uphole of the restriction; and

(e) filling the riser uphole of the restriction with a lighter fluid than the returning fluid to provide a fluid pressure gradient to the wellbore that is less than the pressure gradient formed by the fluid downhole of the restriction.

55. The method of claim 54, wherein pumping the fluid includes pumping with an active pressure differential device ("APD Device").

56. The method of claim 55, wherein the APD Device is one of: (i) at least one centrifugal pump; (ii) a turbine; (iii) and (iv) a positive displacement pump.

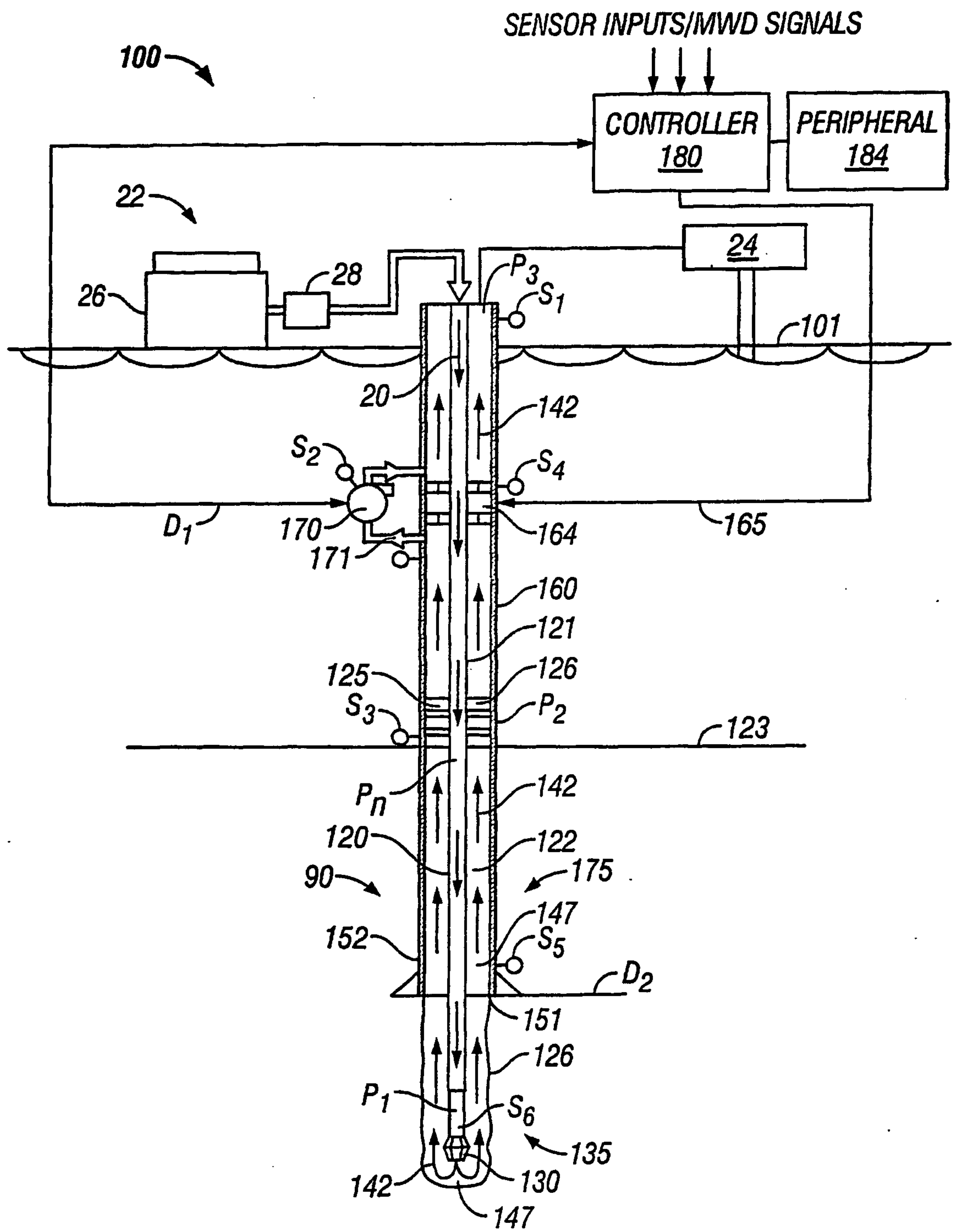
57. The method of claim 54 further comprising providing a separate return line outside the riser and extending to the surface to carry the returning fluid to the

surface while bypassing the riser.

58. The method of claim 54 further comprising controlling the APD Device to create a selected pressure differential across the APD Device.

59. The method of claim 14 further comprising providing at least one pressure sensor to provide signals indicative of pressure in the wellbore, the at least one pressure sensor location being selected from a group consisting of: (i) the annulus of the wellbore; (ii) a location in the drill string; (iii) well control equipment; (iv) the riser; (v) a bottomhole assembly carrying the drill bit; (vi) the surface; (vii) a memory; and (viii) near the inlet of the APD device.

60. The method of claim 19, wherein controlling the APD Device includes one of: (i) maintaining bottomhole pressure at a certain value; (ii) maintaining bottomhole pressure within a range; (iii) maintaining wellbore at at-balance condition; and (iv) maintaining wellbore at underbalance condition.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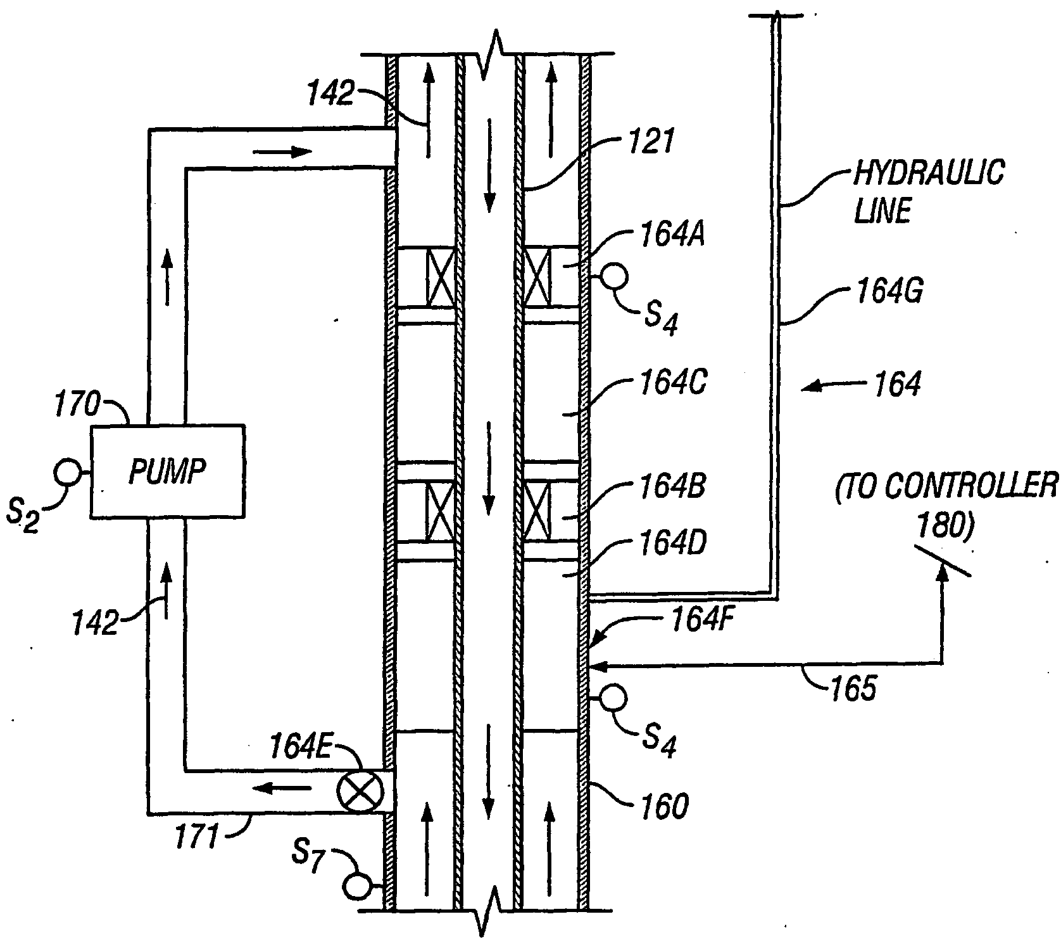
147

FIG. 1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S_7

FIG. 2

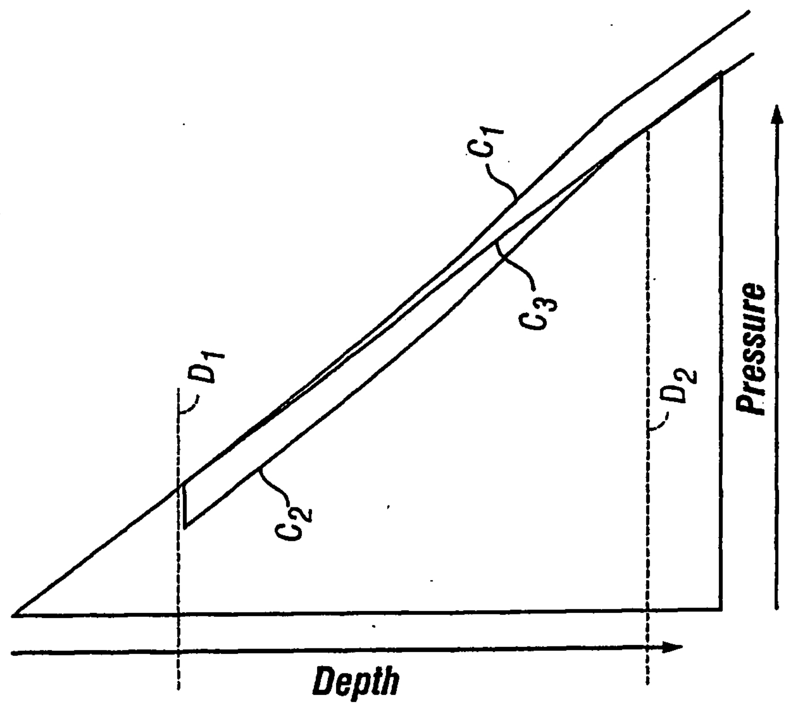

FIG. 3B

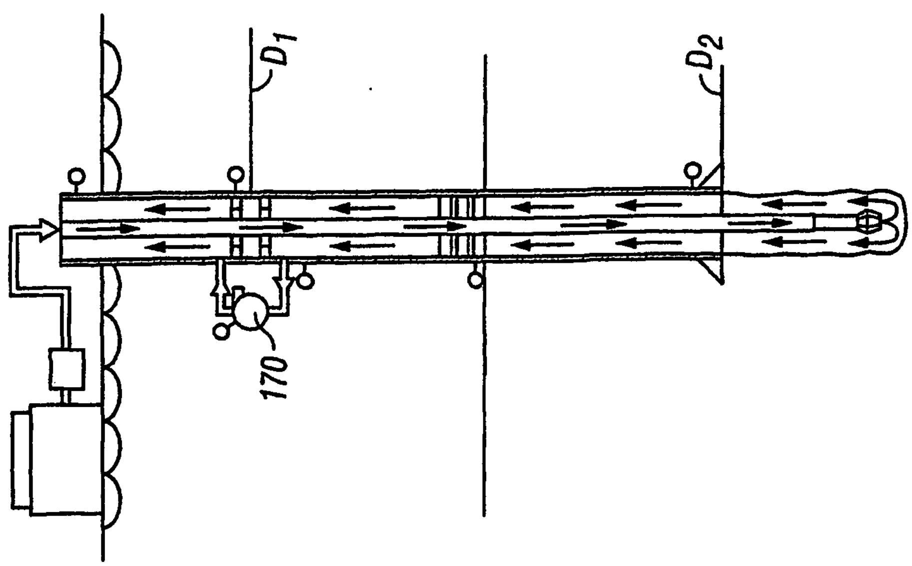

FIG. 3A

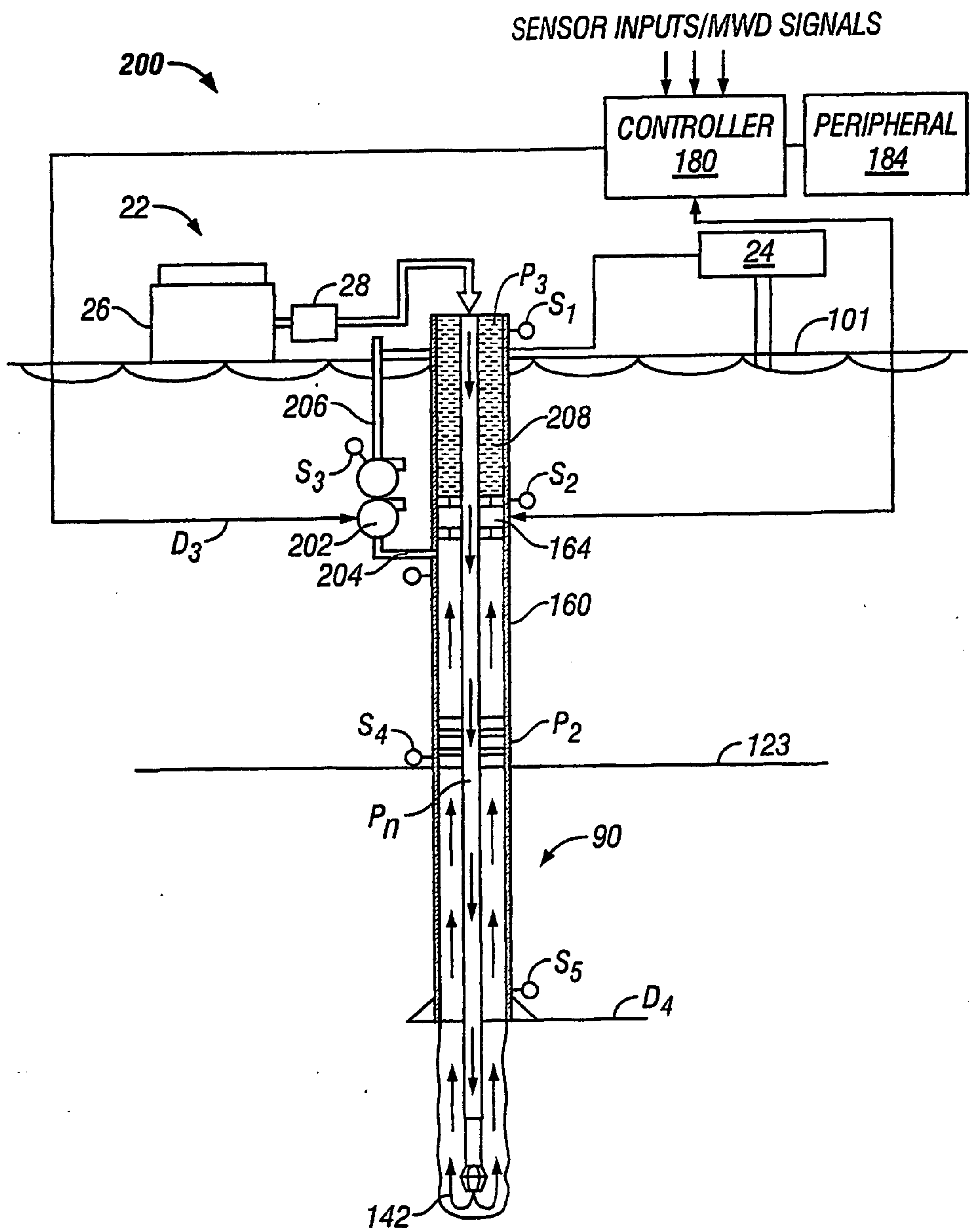
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FIG. 4

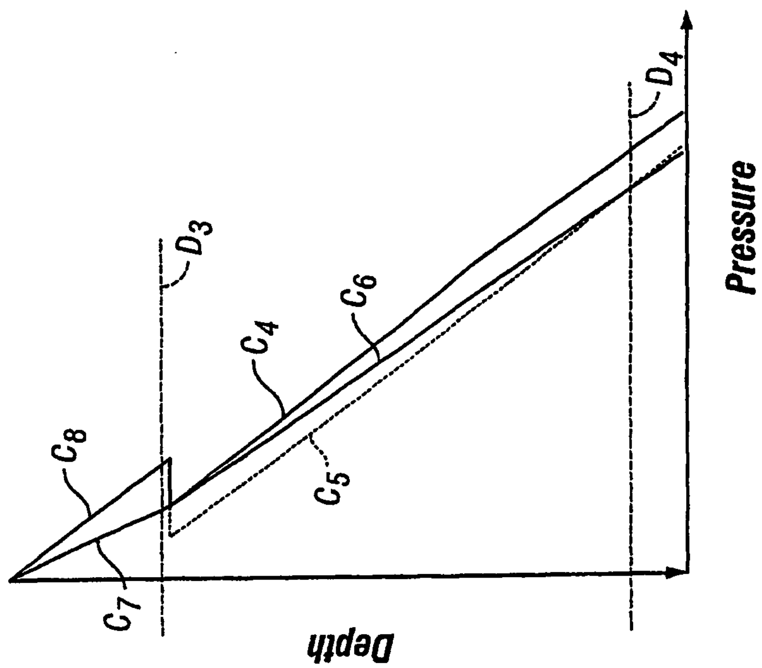

FIG. 5B

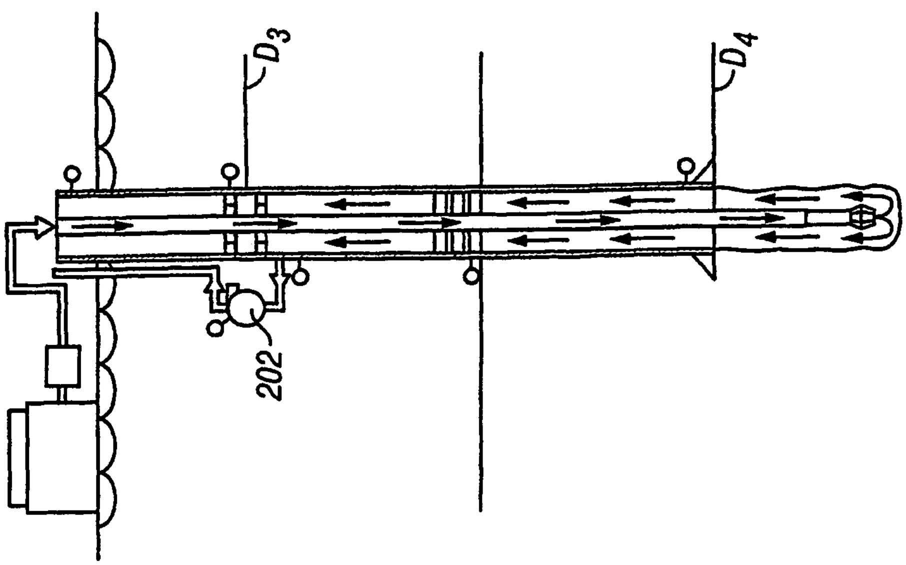

FIG. 5A

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/21520

A. CLASSIFICATION OF SUBJECT MATTER

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
Name and mailing address of the ISA/ Facsimile No.	Authorized officer Telephone No.